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Vision and advocacy of optoelectronic technology developments in the AECO sector

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ABSTRACT

Purpose: This research presents a literature review of laser scanning and 3D modelling devices, modes of delivery and applications within the architecture, engineering, construction and owner-operated (AECO) sector. Such devices are inextricably linked to modern digital built environment practices, particularly when used in conjunction with as-built building information modelling (BIM) development. The research also reports upon innovative technological advancements (such as machine vision) that coalesce with 3D scanning solutions.

Design: A synthesis of literature is used to develop: a hierarchy of the modes of delivery for laser scan devices; a thematic analysis of 3D terrestrial laser scan technology applications; and a componential cross-comparative tabulation of laser scan technology and specifications.

Findings: Findings reveal that the costly and labour intensive attributes of laser scanning devices have stimulated the development of hybrid automated and intelligent technologies to improve performance. Such developments are set to satisfy the increasing demand for digitisation of both existing and new buildings into BIM. Future work proposed will seek to: review what coalescence of digital technologies will provide an optimal and cost effective solution to accurately reconstructing the digital built environment; conduct case studies that implement hybrid digital solutions in pragmatic facilities management scenarios to measure their performance and user satisfaction; and eliminate manual remodelling tasks (such as point cloud reconstruction) via the use of computational intelligence algorithms integral within cloud based BIM platforms.

Originality: Although laser scanning and 3D modelling have been widely covered *en passant* within the literature, scant research has conducted an holistic review of the technology, its applications and future developments. This review presents concise and lucid reference guidance that will intellectually challenge, and better inform, both practitioners and researchers.

KEYWORDS

Laser scanning, digital built environment, building information modelling (BIM), machine vision

INTRODUCTION

Optoelectronics has its etymological roots grounded in physics and encompasses the study, design and manufacture of electronic devices for emitting, modulating, transmitting and sensing light (Sergiyenko and Rodriguez-Quiñonez, 2016). Optoelectronic devices gather and display information at high speed but can also store and process information (Marzuki, 2016). Beneficial characteristics of these devices include their: small and portable size (Faro, 2004); highly sophisticated functionality (Marzuki, 2016); solid-state robustness (Lindner, 2016); and low-power consumption during operation (Faro, 2004). Such attributes have engendered the proliferation of optoelectronic devices throughout society, business and commerce (Rushmeier, 2002). Amongst the hierarchy of optoelectronic technologies available, optical laser scanners are frequently used for the rapid automation of millimetre precision measurement and reconstruction of tangible objects via processed optical signals from reflected light (Thiel and Wehr, 2004). Laser scanning applications are myriad throughout a disparate range of industries, including: aerospace for structural health monitoring (Derriso *et al.*, 2016); law enforcement for virtual crime scene reconstruction (Buck *et al.*, 2013); agriculture for crop growth monitoring (Cointault *et al.*, 2016); archaeology for re-constructing archaeological artefacts (Galeazzi *et al.*, 2016); and manufacturing industries for quality assurance purposes (Godin *et al.*, 1994; Mello and Stemmer, 2016). Given this strong demand, the laser scanning industry's value is forecast to exceed 5.90 Billion USD by 2022 (Markets, 2016).

The architecture, engineering, construction and owner-operated (AECO) sector encompasses the whole life cycle of buildings and infrastructure within the built environment. Within this sector 3D laser distance and ranging (LiDAR) devices rapidly construct point cloud data sets that precisely measure large volumes of physical objects, transcribed into a digital built environment (Chen *et al.*, 2015). Laser scan devices are now integral within numerous built environment applications including: construction progress tracking (El-Omari and Moselhi, 2008); quality control assessment (Wang *et al.*, 2016); site activity monitoring (Zhang *et al.*, 2016); safety assessment (Shapira *et al.*, 2014); and resource and material tracking (Szweda, 2006). Laser scanning also represents an ideal technological solution for automating as-built

Building Information Modelling (BIM) validation (and model updates) for contractors and facility managers (Hoffmeister, 2016). However, whilst demand has grown, laser scan technology is not universally adopted in contemporary AECO practice because of issues pertaining to: high equipment costs (Rushmeier, 2002; Qin and Gruen, 2014); costly human resource training needed to acquire core competencies to operate the laser scanning equipment (Ouédraogo *et al.,* 2014); discrepancies in spatial information (Tang and Akinci, 2012a, 2012b; Jung *et al.*, 2014; Laing *et al.*, 2015) lack of automation with BIM object recognition from point cloud data (Ouédraogo *et al.,* 2014); timely calibration of scanning equipment (Kim *et al.*, 2015a); limited point cloud capture from occlusions (Xiong *et al.*, 2013); and excessive time consumed with point cloud data processing (Golparvar-Fard *et al.*, 2011). In addition, laser-scanning applications integrated with BIM lack automation in the recognition of semantic attributes from scanned data – albeit point cloud semantic recognition has accrued maturity in factory automated scanning of small objects (Rushmeier, 2002; Godin *et al.*, 2010).

To address these limitations, research and industry practice advocate using automated image-based sensing technologies to augment laser scan technology (Golparvar-Fard *et al.*, 2011). Machine vision enhances laser scan capabilities through object recognition and description, utilising algorithms for image processing and pattern recognition (Gao *et al.*, 2015). Such advancements have been successfully applied within the manufacturing, automotive and security industries – hence, advanced technology transfer into the AECO sector is feasible (Flores-Fuentes *et al.*, 2016). The wider applications of integrated scanning-software devices represent the next generation of revolutionary technological solutions adopted throughout a building's entire life cycle (Turkan *et al.*, 2014). Hitherto, research has not reported upon suitable automated image/laser-based reconstruction to manage and update the as-built BIM for both new build development and/or retrospective modelling. Against this contextual backdrop, this literature review aims to: i) provide a qualitative, componential analysis of current as-built image/laser-based reconstruction devices and applications used to maintain digital built environment data; ii) critically evaluate contemporary laser scanning and automated machine vision processing developments; and iii) propose a future trajectory for augmented laser scanning devices in the AECO sector.

FUNDAMENTALS OF LASER-SCAN DEVICES

Optoelectronic scanning devices have developed rapidly since initial laboratory testing was conducted by the National Research Council of Canada (NRCC) during the 1970s (Blais, 2004) (refer to Figure 1). 3D laser scanning initially lagged behind 2D laser scanning technologies in terms of image quality, rendering and ease of use (*ibid*). However, the advent of microcomputers and exponential improvements in computational processing power transformed 3D laser scanning to mirror the performance of its counterpart (Sergiyenko and Rodriguez-Quiñonez, 2016). These technological breakthroughs have stimulated the development of cost-effective, automated, contactless 3D range sensor systems for various industrial applications (Hornberg, 2006). Since the early 1980s, three generic contactless methods of range measurement have emerged, namely: i) triangulation; ii) phase shift; and iii) time of flight (TOF) or pulse-based – albeit, a number of hybrid scanning devices integrate multiple methods (e.g Moiré pattern projection and fringe interference) (Creath and Wyant, 1992).

Triangulation

Triangulation is suitable for short-to-medium distance measurements (<5-10 m). An early example of triangulation based 3D laser cameras are slit scanners due to their optical and mechanical simplicity and cost (Galantucci *et al.,* 2015). Slit-scanners utilise an angled light line projected onto the target object; deformation of the straight-line projection provides information about the target surface protuberances (Hornberg, 2006). This method is limited in capacity for large volume capture since short-range slit scanners are a compromise between field of view and depth resolution (*ibid*). They are typically limited to a field of view of between 20-50 degrees.

Phase shift

Phase shift devices calculate the difference between the overlapping sent and reflected signal(s) within a certain wavelength (Lindner, 2016). This offers speedy measurement in comparison with TOF methods but the output point cloud data does suffer from higher speckle noise interference (Creath and Wyant, 1992; Beraldin *et al.,* 2000a). Whilst speckle noise can be reduced with good lighting conditions, such instances are rare on construction sites, particularly when laser scanning larger objects such as buildings (Godin *et al.*, 2010).

Time of flight

Time of flight (TOF) is suitable for long distance range measurement (10-25m) and utilises multiple single laser point reflections. By recording the time taken for millions of laser pulses to return to the sensor the distance can be calculated (Blais *et al.*, 2000). Multiple iterations of reflection propagate a vast yield of points in space, commonly referred to as point cloud data, which represent Cartesian coordinates that are processed to create a 3D model of physical objects (Gao *et al.*, 2015). The primary benefits of TOF laser scanning include an ability to quickly assimilate the measurement of large surface areas to a millimetre-level accuracy and precise spatial resolution (El-Omari and Moselhi, 2008). TOF scanners are widely adopted in the AECO sector because they capture larger range, broader field of view and higher resolution. TOF generates 3D data with an accuracy typically within 2–6 mm at 50 m and high point density up to 1,000,000 points per second (Faro, 2004) (refer to Table 1). Accuracy and range of TOF scanners are restricted by physical limitations such as speckle noise and optical resolution (Shoji, 2013).

Hybrids

By the 1980s, a range of short-, mid- and long-range 3D laser scanning devices had been developed, such as pattern projection scanners (which use either phase shift, TOF or triangulation) (Beraldin *et al.*, 2000b). Pattern projection (aka structured light 3D scanning) uses multiple stripes or patterns projected onto a target, rather than scanning a single laser line of point onto the object surface and processing the independent profiles retrospectively (Blais, 2004). Pattern projection scanners are limited to short-range scanning (circa 10-15m range) (Lindner, 2016).

COST, SPECIFICATIONS AND MODES OF DELIVERY

The exorbitant cost of commercially available equipment is a fundamental obstacle for the purchase of 3D laser scanning devices within the AECO sector (Galantucci *et al.*, 2015). Costs fluctuate depending upon the device's specification (*ibid*). Table 1 presents a qualitative, componential specification analysis of the three primary modes of conducting short-, mid- and long-range TOF laser scanning during construction and post-construction stages, namely: i) airborne; ii) mobile; or iii) terrestrial (refer to Figure 2). The criteria analysed are: number of points being generated; range of scan; weight; ranging error; optical resolution; field of view; price range; and laser class. Range of scan is the minimum measurable distance in an indoor-outdoor environment at an upright incidence to a surface with 90% reflective material. Ranging error is the degree of conformance between a measurement of an observable quantity and a recognized standard or specification that indicates the true value of the quantity (Blais *et al.*, 2000). Optical resolution is the minimum dimension of an object feature that the 3D scanner can acquire (Faro, 2004). Field of view is determined by the angle of laser scan capture capabilities between 20-360 degrees vertically. Laser class is defined by International Electrotechnical Commission (IEC) document 60825-1 I, which assigns lasers into one of four hazard classes (1, 1M, 2, 2M, 3, 3M, 4, in ascending order - 1 being the least harmful).

Airborne Laser Scanning

Airborne laser scanning (ALS) devices measure the range of reflected objects on the earth's surface for numerous mapping applications including: railway tracks; waterway landscapes; and electrical transmission lines (Wehr and Lohr, 1999). Airborne scanners have evolved from early applications in aerospace with satellites to the more widely adopted geological and agricultural surveys (Andujar *et al.*, 2011; Lehtomäki *et al.*, 2015). LiDAR systems are used in ALS to track geo-referenced points from the terrain (Cointault *et al.*, 2016). ASL devices overlap with unmanned devices such as unmanned aerial vehicles (UAV's) (Irizarry and Costa, 2016).

Mobile Laser Scanning

Mobile laser scanning (MLS) devices that are fitted to vehicles continuously scan whilst in motion to capture a huge volume of point data (Breuckmann, 2014; Qin and Gruen, 2014). Most mobile scanning devices include LiDAR capabilities to capture transport infrastructure. Construction professionals can also carry/wear MLS devices to harness laser scan data whilst manoeuvring around site (Longstreet, 2010). Hand-held devices are compact and cheaper but have a limited scanning range, where 1 millimetre accuracy is only achieved at a 1 metre range from the target object (Faro, 2004). Mobile scanning devices such as FARO *Freestyle3D*, Leica *Pegasus: Two* and Leica *Pegasus: Backpack* require expensive manned management to control either the vehicle, hand-held device or backpack unit (Lehtomäki *et al.,* 2015). MLS devices can also provide machine vision for navigating and orientating autonomous robots (Association, 2007; Lindner *et al.*, 2016). Such use is rare in the AECO sector and currently the major original equipment manufacturers do not offer such devices.

Terrestrial Laser Scanning

Terrestrial Laser Scanning (TLS) technology is the preferred method for scanning ground based discrete objects because it captures static 3D objects with high accuracy (Bosché *et al.*, 2015). Limitations of 3D TLS scanning include: the time required to perform a single high-resolution scan; the number of scan-locations required to capture an entire site or building; the high costs of equipment operation; and its stationary nature that limits both the scanning capacity with limited field of view and potential loss of data via occlusions (Godin *et al.*, 2010;) Bosché *et al.*, 2015; Brilakis *et al.*, 2010). Leica and FARO TLS models differ in range capabilities and price – for example, the *Leica C10* is reasonably affordable but accuracy performance and range are lower (refer to Table 1). Lower specification models available are more suited to as-built and topographic high-definition surveying applications but are more harmful to humans with a laser classification of 3R.

LASER SCANNING APPLICATIONS

To undertake a thematic literature review of TLS technology applications, a keyword search was conducted (using 'laser scan' or laser-scan' as the search terms) across several prominent journal databases such as Emerald and Science Direct. Relevant journal papers were then categorised into four thematic groupings, namely: progress tracking; quality assessment; structural health monitoring; and development of as-built data (refer to Figure 3). Within each theme, the frequency of published work is presented by industry sector (architecture, engineering, construction, operations and other).

Progress Tracking

Progress tracking is a prerequisite requirement for the effective and efficient cost management of labour, plant and equipment, and materials (El-Omari and Moselhi, 2009). Traditionally, tracking progress on a construction site has been achieved through video footage (Meadati *et al.*, 2010). More recently, laser scanning technology (such as LiDAR) has been utilised to capture data for progress monitoring, therefore enabling the integration of as-designed development via BIM (Matthews *et al.*, 2015). LiDAR is particularly suited for tracking structural work progress and quality because it can reproduce 3D information with millimetre precision. The limitations of LiDAR when compared to traditional methods (such as video footage) are its high purchase cost and inability to directly monitor dynamic points of interest such as labour, materials and equipment. Dynamic components are better monitored by RFID tags which track the location and movement of machines and workers to capture their productivity and safety performance (Motamedi *et al.*, 2013; Bosché *et al.*, 2015). Barcodes are inexpensive and useful for progress monitoring static materials and equipment in the supply chain (i.e., at prefabrication and laydown yards) (El-Omari and Moselhi, 2009). However, applications in practice have declined because barcodes are easily damaged and incapable of geo referencing (Lindner, 2016). Digital photography and video footage are also limited in their scope to accurately capture meteorological conditions, construction work progress and resource movement (Riaz *et al.*, 2006).

Quality Control and Assessment

Quality control and assessment within the AECO sector has been adopted predominantly to determine the integrity of existing structural elements - henceforth, evidence of application in the post-construction stages of operations and maintenance (O&M) is limited (Kim *et al.*, 2015a). Structural engineers can validate steel frames, pre-cast and cast in situ concrete structural elements with laser scanning and post inspection of final point scan data (Zeibak-Shini *et al.*, 2016). Redundancy of points poses an issue due to the excessive time taken during the production of point clouds and has led to the development of innovative automated quality assessment methods and procedures (Park *et al.*, 2007). For example, TLS devices have been deployed to estimate dimensions of pre-cast concrete elements with geometric irregularities by cross referring the data with as-designed BIM data (Wang *et al.*, 2016). TLS devices are the preferred choice for conducting quality assessment and have been applied in: structure deformation measurement (Monserrat and Crosetto, 2008); dimensional estimation (Wang *et al.*, 2016); and identification and quantification of surface damage (Olsen *et al.*, 2010). To further augment this process, photogrammetry has been adopted in quality assessment, either independently or combined with TLS (Scaioni *et al.*, 2014).

Structural Health Monitoring

Structural health monitoring using laser scanning devices is widely used throughout industry (Barazzetti *et al.*, 2015) including: aerospace engineering (Derriso *et al.*, 2016); structural engineering (Park *et al.*, 2013); geological engineering (Scaioni *et al.*, 2014); and archeological surveying (Godin *et al.*, 2010; Galeazzi *et al.*, 2016). Structural engineers have similarly adopted workflow in determining structural integrity with pre-cast concrete structures and steel work (Zeibak-Shini *et al.*, 2016). Accuracy of the TLS point cloud data has been used for defect detection for concrete structural elements (Kim *et al.*, 2015b) and piping systems (Safa *et al.*, 2015). TLS devices are used because of their higher accuracy and ability to record surface quality defects (Kim *et al.*, 2013).

TRANSLATING AS-BUILT PROGRESS TO BIM VIA LASER SCANNING

Adopting digital technologies can enhance as-built data (both geometric and semantic) for both new build and retrospective BIM (Love *et al.*, 2014; Patacas *et al.*, 2015). For example, recent research demonstrated how rich semantic data can be integrated and visualised within a new build as-built BIM using bar code scanners linked to totems (cf. Pärn and Edwards, 2017). Totems were built using an application programming interface (API) plug-in to visualise rich semantic data in a 3D object and extend the use and application of COBie (*ibid*). The main benefits for contractors of as-built BIM capture via laser scan technology are: early identification of nonconformities between the as-built and as-designed situations (Bosché *et al.*, 2015); faster approval of work by the main contractor so that sub-contractors receive timely payment (Klein *et al.*, 2012); and handover of contemporary as-built BIM to the client and/ or facilities management team (Matthews *et al.*, 2015). The facilities management team (FMT) can also harness substantial benefits during the O&M phase of building asset management (Pärn, et. al., 2017). These benefits include: an ability to update and maintain an accurate as-built BIM; and access building specification information via a centralised as-built BIM repository (linked though barcode, radio frequency identification (RFID) tags or quick response (QR) codes – cf. Pärn and Edwards, 2017).

Although various studies demonstrate successful implementation of laser scan technologies by contractors for site reconstruction (Bosché, 2010; Zhang and Arditi, 2013; Wang *et al.*, 2015), the formation of a semantically rich BIM model eludes the AECO sector due to the difficulties of transforming the raw point cloud data (Pătrăucean *et al.*, 2015). The process is labour intensive and prone to human error (Xiong *et al.*, 2013). Semantic information vis-a-vis geometric is essential for the FMT to substantiate O&M for building assets; current methods of integrating point cloud data with BIM fail to fulfil this requirement (Pătrăucean *et al.*, 2015). While extant literature is replete with studies that examine as-built development (Bennett, 2009; Longstreet, 2010; Huber *et al.*, 2011; Kim *et al.*, 2013; Barazzetti, 2016), studies that provide guidance/decision support on selecting suitable enabling digital technology and techniques remain deficient. Primary reasons for such disparity are attributed to a: i) lack of case studies on the utilisation of as-built BIM by the FMT (Becerik-Gerber *et al.*, 2011; Hungu, 2013); and ii) paucity of research identifying successful processes for as-built BIM development using laser/image based 3D reconstruction. Whilst recent research has predominantly focused upon automatic 3D object recognition to automate the integration with as-built BIM, commercial tools currently available offer semi-automated options only (Chen *et al*., 2015). More recent developments that utilise 3D modelling via photogrammetry, suggest a possible paradigm shift towards machine vision applications.

Most literature on automated 3D modelling revolves around construction stage related activities and phases (Chen *et al*., 2015; Galantucci *et al*., 2015). Yet this geometrical representation of physical construction is insufficient – as Törmä (2013) proffers, more attention should be focussed upon creating semantic detail in as-built models for the purpose of accurately emulating physical assets. Although point cloud scans can provide a geometric cross reference between the physical and the virtual space, this does not emulate the much needed semantic level of information required by contractors, designers, engineers and the FMT (Tang *et al*., 2010; Akanmu and Anumba, 2015).

Post Processing and Information Retrieval

Post processing algorithms and applications provide an opportunity to deliver automated 3D laser scanning reconstruction of the as-built BIM with some degree of semantic information (Sturm and Triggs, 1996; Szeliski, 2010). Utilising computational algorithms to determine or identify attributes from massive point cloud data has been applied in structural engineering, construction and design stages (Brilakis *et al*., 2010; Xiong *et al*., 2013; Barazzetti, 2016; Lindskog *et al*., 2016). Applications of computational algorithms include: tunnel cross section dimensional quality assessment (Han *et al.* 2013); deformation measurement results for concrete structures (Gordon and Lichti, 2007); and volume loss estimation for an in-situ concrete bridge (Liu *et al.,* 2011). Analysis and post-processing of point cloud data expedites interpretation of the massive yield of points into a usable format for existing workflows such as BIM. Post processing tools have automated the generation of new 3D objects directly into the BIM authoring platform particularly for complex mechanical electrical and plumbing (MEP) projects which comprise of hundreds of intricate piping systems (Brilakis *et al*., 2010; Barazzetti *et al*., 2015; Son and Kim, 2016).

Bosch *et al*., (2008; 2010; 2015) first coined the term 'Scan-vs-BIM' technique where point cloud data is compared to as-designed models. The adversarial Scan-vs-BIM definition assumes that BIM merely acts as a separate point of reference for point cloud data (Son *et al.*, 2015). This manual workflow adopts a three stage process, namely: i) multiple scans are captured from different TLS stations; ii) point cloud data from these multiple scans is integrated through a process known as registration; and iii) BIM is employed to author new objects using the point scans as a reference (Monserrat and Crosetto, 2008; Wang and Cho, 2015). Semi-automated, post processing software can expedite this process, but the procedure lacks integration and full automation (Bosché, 2010; Hyojoo Son, 2015). A more comprehensive definition of this process is the 'Scan-to-BIM' method, which incorporates semi-automated post processing software packages, enabling faster model reproduction time. Hence, Scan-to-BIM provides a more suitable definition for the coupling of BIM with laser scanning technologies. Current literature regarding case uses and applications of Scan-to-BIM during the O&M stages remain sparse despite recommendations that endorse handover of the as-built BIM model to the FMT (CRC Construction Innovation, 2007; Eastman *et al.*, 2011; Teicholz, 2013; Love *et al.*, 2015). In a narrow sense, BIM represents a 'central information management hub'(Volk *et al.*, 2014) – however, BIM cannot become a static information repository created by its corresponding designers, otherwise it becomes 'blind' to the on-going vicissitudes of asset management (Chen *et al.*, 2015). As-built data collection augmented by rapid laser prototyping and BIM integration will generate a more realistic account of assets during the design-construction (Matthews *et al.*, 2015) and post-construction (Volk *et al.*, 2014) stages.

AUGMENTING LASER SCANNING WITH MACHINE VISION

The AECO sector is currently confronted by the fourth industrial revolution, known as 'Industry 4.0' where cyber-physical production systems (CPS), automation, data exchange and manufacturing technologies coalesce (Perez *et al.*, 2016). To keep abreast of such developments, practitioners must seek guidance from other more technologically advanced industries on how to better integrate widespread digital data exchange and automation in digital data reproduction (i.e. BIM) (Koutsoudis *et al.*, 2014; Zou *et al., 2016*). Machine vision (aka 'industrial vision' or 'vision systems') provides automation in the mundane manufacturing tasks of inspection and fault detection with broader applications automating collision detection in autonomous moving vehicles and robotics (Riaz *et al.*, 2006). Machine vision is achieved through the integration of laser scan data, photography and software algorithms used for post processing (Sergiyenko and Rodriguez-Quiñonez, 2016). Given the advent of the digital built environment and rapidly emerging technologies such as laser scanning, new opportunities for machine vision within the AECO sector simultaneously emerge (e.g. site monitoring).

Embryonic machine vision developments within the AECO sector have integrated laser scan technology (Son *et al.*, 2015) and photogrammetry (Scaioni *et al.*, 2014). Photogrammetry is used in progress monitoring on construction sites because it is cost efficient and merely requires still or moving photographic data in conjunction with automated reconstruction software (*ibid.*). One example of the practical application of the integrated solution is merging 3D TLS data with photogrammetry for post asset inspection purposes (Monserrat and Crosetto, 2008). Others such as El-Omari and Moselhi (2009) have demonstrated improved site progress capture and monitoring with the combination of photogrammetry, laser scanned point cloud data and post processing software PHIDIAS. This hybrid development monitored and reported upon construction progress with an impressive 75% reduction in the time needed to scan a site (*ibid.*). However, Golparvar-Fard *et al.*, (2011) revealed that the work of El-Omar and Moselhi (2008) could be enhanced by integrating accurate geo-referenceable site coordinates with photographic content. Integration provides a much-needed semantic link between photogrammetry and point cloud data (*ibid*), thus enabling remote decision making by contractors based on the as-designed information (Koutsoudis *et al.*, 2014; Safa *et al.*, 2015). These techniques are heavily founded upon the Structure-From-Motion (SfM) and Dense Multi-View 3D Reconstruction (DMVR) algorithms and newly developed photogrammetry applications are now commercially available (*ibid*). SfM and DMVR algorithms automate 3D modelling generation from an unordered image collection of the target object from multiple viewpoints (Sturm and Triggs, 1996). The difference in SfM lies in the 'calibration' process, where the internal camera geometry parameters, external camera position and orientation are automatically adjusted using correspondences between the image features (Peters, 2010; Szeliski, 2010). SfM uses a 3D structure of the environment and camera motion within the scene to automate 3D modelling (Szeliski, 2010). Where 3D laser scanning technology is an expensive technology, image processing SfM and DMVR software is cost-effective and efficient (cf. Golparvar-Fard *et al.*, 2011). As these technological innovations continue to coalesce, the management of built environment assets will become increasingly reliant upon machine learning and automated decision making to fully exploit a vast array of structured geometric and semantic data. Machine learning algorithms will expand the capabilities of laser scanning devices during operations and maintenance of assets within the built environment and in turn, improve business profitability and performance.

CONCLUSIONS

The digital built environment era has created huge demand for laser scanning technology to improve the performance and efficiency of project management throughout an asset's life cycle. When coupled with other digital innovations such as BIM, laser scanning provides an ideal solution to rapidly creating and updating as-built BIM models. However, anecdotal user experience of these technologies reveals that although they represent an improvement upon traditional means of reconstructing the built environment, challenges doggedly persist. These challenges include the: high cost of point cloud reconstruction processing time; considerable investment needed to train and upskill personnel to use advanced technologies effectively; and lack of automation of semantic attributes within BIM. Automation is needed to transform raw point scan data into semantically rich BIM model data; such a process will remove the need for laborious manual procedures and mitigate the propensity to introduce human error. Readily available semantic information in a digestible and accessible format is crucial for clients and the FMT who manage building assets post construction – this requirement is set to grow in prominence given the UK government's mandate to deliver projects to a BIM Level 2 standard.

Many issues facing the AECO sector have already been partly or wholly resolved within other sectors such as forestry, aviation and automotive; a period of extrospection is advisable to reconsider whether technology/knowledge transfer could resolve these challenges. For example, in forestry laser scanning is used to maintain and manage ecosystems – a similar approach could be adopted to maintain built environment assets. In addition, it would appear that OEMs have developed a bespoke array of commercial products driven by poorly defined customer specifications and commercial gain. A number of BIM platforms, 3D scanners and complementary standalone software packages have evolved in an ad-hoc manner to meet an insatiable demand. This uncontrolled burst of technological development now requires a reflective period of amalgamation and rationalisation of technologies. For example, coalescence of photogrammetry, machine vision, post processing algorithms and 3D laser scanning technologies could provide the next generation of optimal and cost effective solutions to accurately reconstruct, track and monitor the digital built environment throughout its entire life cycle. Case studies are also required to validate the implementation of these hybrid digital solutions in pragmatic facilities management scenarios to gauge performance and user satisfaction. Specifically, such work should seek to eliminate manual remodelling tasks (e.g. point cloud reconstruction) via the use of computational intelligent algorithms integral within cloud based BIM platforms.

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Figure 1 – Laser Scan Device Evolution Timeline

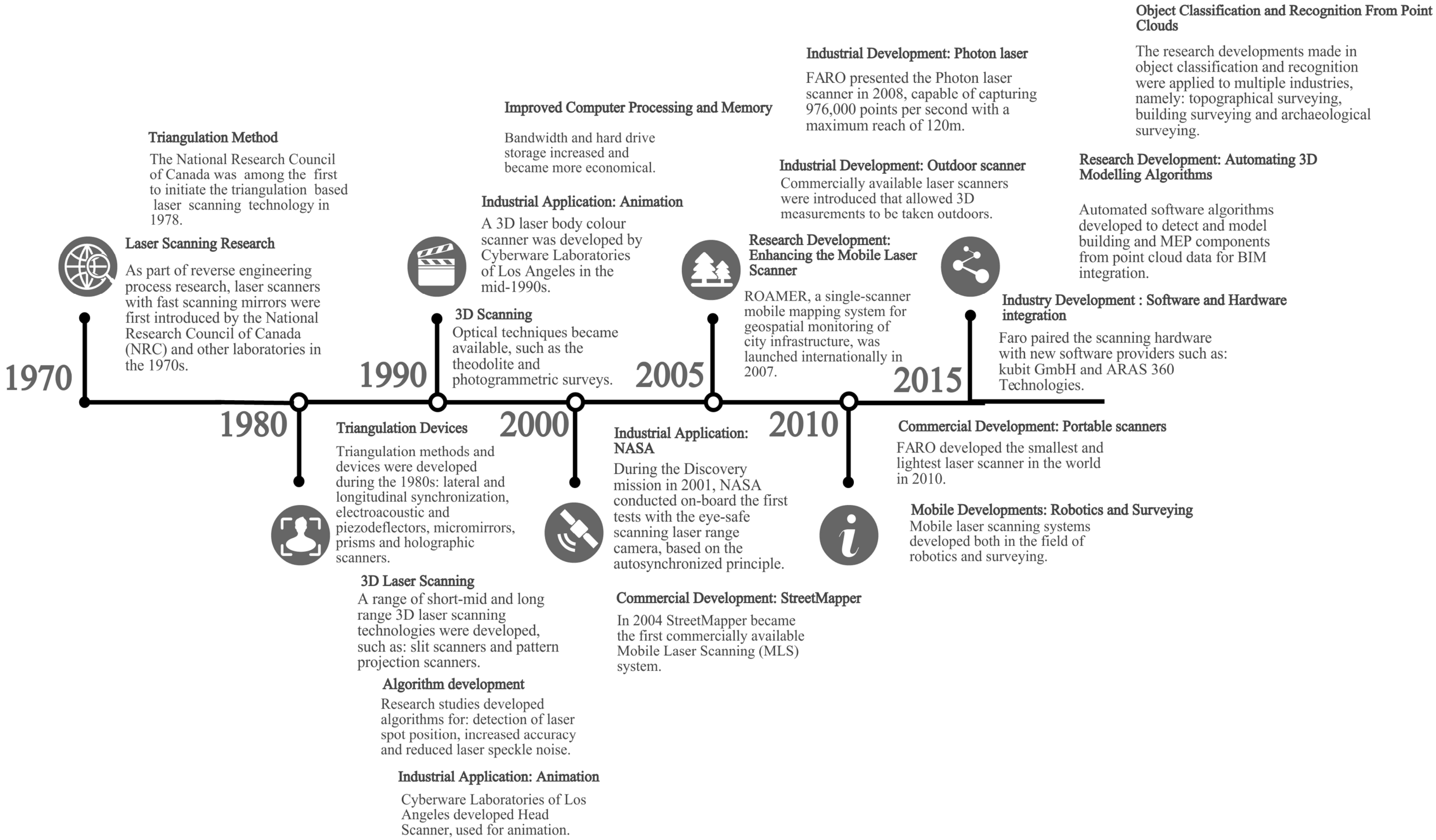


Table 1 - Componential Specification Tabulation of Laser Scan Technology

Specification / Models/Brand	Number of Points			Range of Scan/ Min Range				Weight			Range Error*			Resolution			Field of View			Price Range			Laser Class		
	2000-50,000	50,000-500,000	500,000 – 1 million	0.3-3m	3-50m	50-130m	130-330m	≤2.5kg	2.5-25 kg	25-110 kg	±35µm±80µm	±1mm	±2mm	≤100 megapixels	100-170 megapixels	≥170 megapixels	≤200°	200-300°	300-360°	≤£50,000	£50,000-100,0000	≥ £100,000	1 -1M	2-2M	3R-3B-4
Airborne Laser Scanning Devices																									
RIEGL-VUXL-1LR	●						●		●				●	●					●			●	●		
RIEGL-VQ-880-G	●						●		●				●	●			●					●	●		
Leica City Mapper Airborne	●						●			●			●	●			●					●	●		
Terrestrial Laser Scanning Devices																									
FARO Focus^{3D} X 30			●		●				●		●				●				●	●			●		
FARO Focus^{3D} X 130			●			●			●		●			●					●	●			●		
FARO Focus^{3D} X 130 HDR			●			●			●				●		●				●	●			●		
FARO Focus^{3D} X 330			●				●		●				●			●			●	●			●		
FARO Focus^{3D} X 330 HDR			●				●		●				●			●			●	●			●		
Leica HDS6100			●			●			●				●			●			●	●					●
Leica Scan Station P30/P40		●					●			●			●			●			●			●	●		
Leica Scan Station P16			●		●				●			●				●			●		●		●		
Leica Scan Station C10	●				●				●				●	●					●		●				●
Leica Scan Station C5	●				●				●				●	●					●		●			●	
Mobile Laser Scanning Devices																									
FARO Freestyle^{3D}	●			●				●			●					●	●			●			●		
Leica Pegasus: Two			●				●			●			●			●			●			●	●		
Leica Pegasus: Backpack			●			●			●				●	●				●			●		●		
Leica Pegasus: Stream			●	●						●			●	●					●			●	●		
RIEGL VMX 450			●	●						●			●	●					●			●	●		

NB: *Range error of commercially available scanners is dependent upon the individual make and model. Vendors define range error as the standard deviation of one sigma (σ), taken from a systematic measurement at around 10m and 25m. Maximum error can exceed 1 sigma, depending on the distance measured (i.e > 25m ± mm) and the reflectivity of the material being scanned.

Figure 2 – Modes of Delivery for Laser Scan Devices

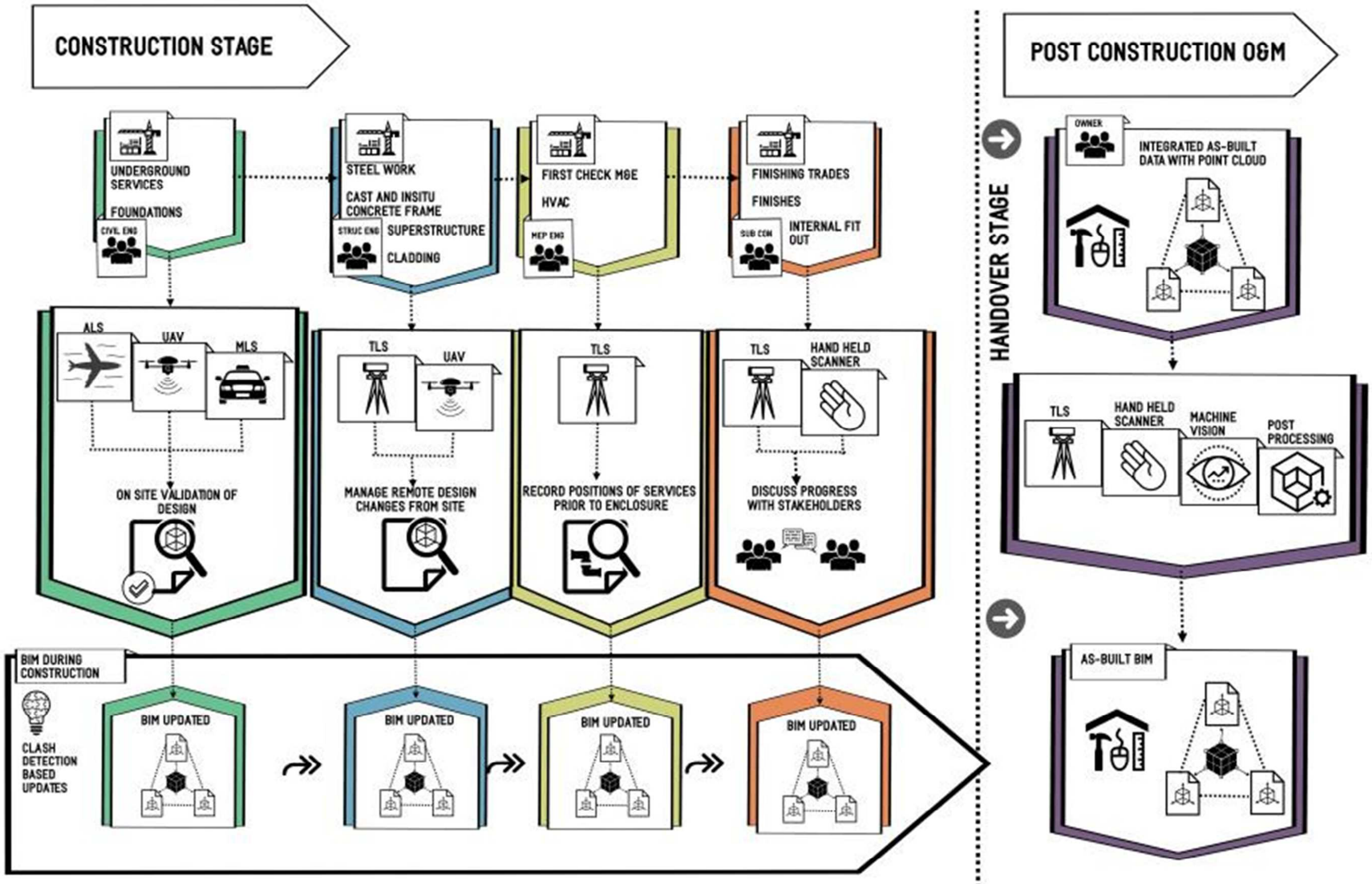
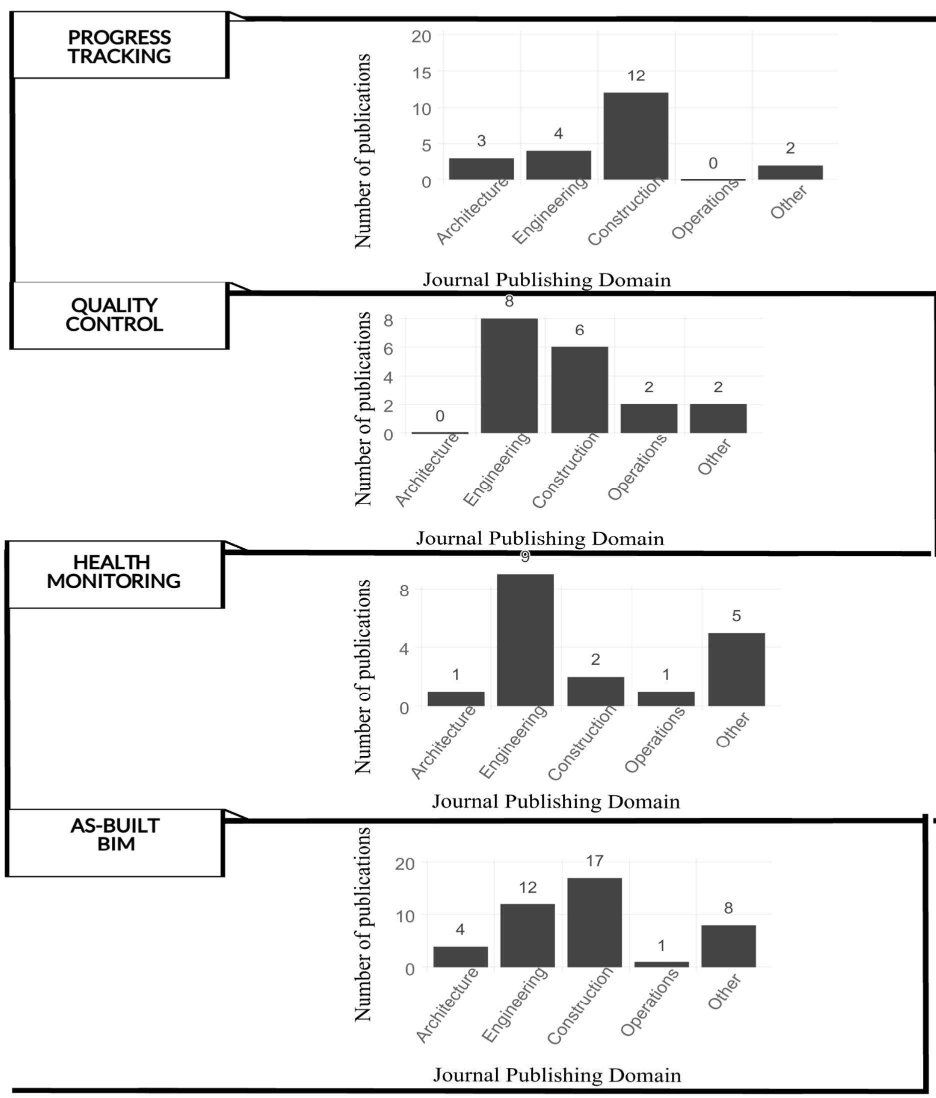


Figure 3 – Thematic Literature Analysis of 3D Terrestrial Laser Scan Technology Applications



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(Akanmu and Anumba, 2015; Bosché, 2010; Bosché et al., 2015; Chen et al., 2015; El-Omari and Moselhi, 2008; El- Omari and Moselhi, 2009; Gao et al., 2015; Golparvar-Fard et al., 2011; Hyojoo Son, 2015; Jung et al., 2014; Kim et al., 2013; Matthews et al., 2015; Pătrăucean et al., 2015; Son et al., 2015; Turkan et al., 2014; Volk et al., 2014; Wang and Cho, 2015; Wang et al., 2016; Zhang and Arditi, 2013; Zou et al., 2016)

(Bosché et al., 2015; Gao et al., 2015; Gordon and Lichti, 2007; Irizarry and Costa, 2016; Kim et al., 2015a; Kim et al., 2015b; Klein et al., 2012; Monserrat and Crosetto, 2008; Olsen et al., 2010; Pătrăucean et al., 2015; Safa et al.; Scaioni et al., 2014; Turkan et al., 2014; Volk et al., 2014; Wang et al., 2016; Zhang et al., 2016)

(Barazzetti et al., 2015; Bosché et al., 2015; Chang and Tsai, 2013; Derriso et al., 2016; Gao et al., 2015; Irizarry and Costa, 2016; Lindner et al., 2016; O'Keeffe and Bosche, 2015; Park et al., 2007; Park et al., 2013; Pătrăucean et al., 2015; Safa et al., 2015; Sumitro et al.; Tang and Akinci, 2012; Wang et al., 2016; Zhang et al., 2016; Zou et al., 2016)

(Akanmu and Anumba, 2015; Azhar, 2011; Barazzetti, 2016; Barazzetti et al., 2015; Bennett, 2009; Bosché, 2010; Bosché et al., 2015; Brilakis et al., 2010; Chen et al., 2015; Ebrahim, 2011; El-Omari and Moselhi, 2008; El- Omari and Moselhi, 2009; Forster et al., 2015; Gao et al., 2015; Golparvar-Fard et al., 2011; Huber et al., 2011; Hyojoo Son, 2015; Jung et al., 2014; Kim et al., 2013; Kim et al., 2015a; Klein et al., 2012; Laing et al., 2015; Laing et al., 2014; Lindskog et al., 2016; Longstreet, 2010; O'Keeffe and Bosche, 2015; Pătrăucean et al., 2015; Perez et al., 2016; Shapira et al., 2014; Son and Kim, 2016; Son et al., 2015; Son et al., 2015 ; Tang and Akinci, 2012a, 2012b; Tang et al., 2010; Turkan et al., 2014; Volk et al., 2014; Wang and Cho, 2015; Wang et al., 2015; Wang et al., 2016; Won and Lee, 2016; Xiong et al., 2013; Zeibak-Shini et al., 2016; Zhang and Arditi, 2013; Zhang et al., 2016; Zou et al., 2016)